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THESIS

AN INVESTIGATION OF THE RESISTANCE PROPERTIES OF A MODERN TRIMARAN COMBATANT SHIP BASED ON TAYLOR STANDARD SERIES AND SERIES 64

by

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ABSTRACT

The resistance properties and effective horsepower requirements for a trimaran being considered for SC-21 (Surface Combatant for the 21st century) are investigated. The effects on EHP due to increased side hull displacement are analyzed. Residual-resistance coefficients are obtained for side hull displacements up to 5% of the center hull's displacement. Coefficients are based on the Taylor Standard Series and Series 64 data. The effects of interference on effective horsepower requirements are discussed. The potential use of Reynolds-averaged Navier-Stokes (RANS) code is presented.

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I. INTRODUCTION

The U.S. Navy is considering several designs for its Surface Combatant for the 21st Century (SC-21). One is the trimaran warship. Such a ship would have a long slender center hull and two outriggers, or side hulls; as shown in Fig. 1.

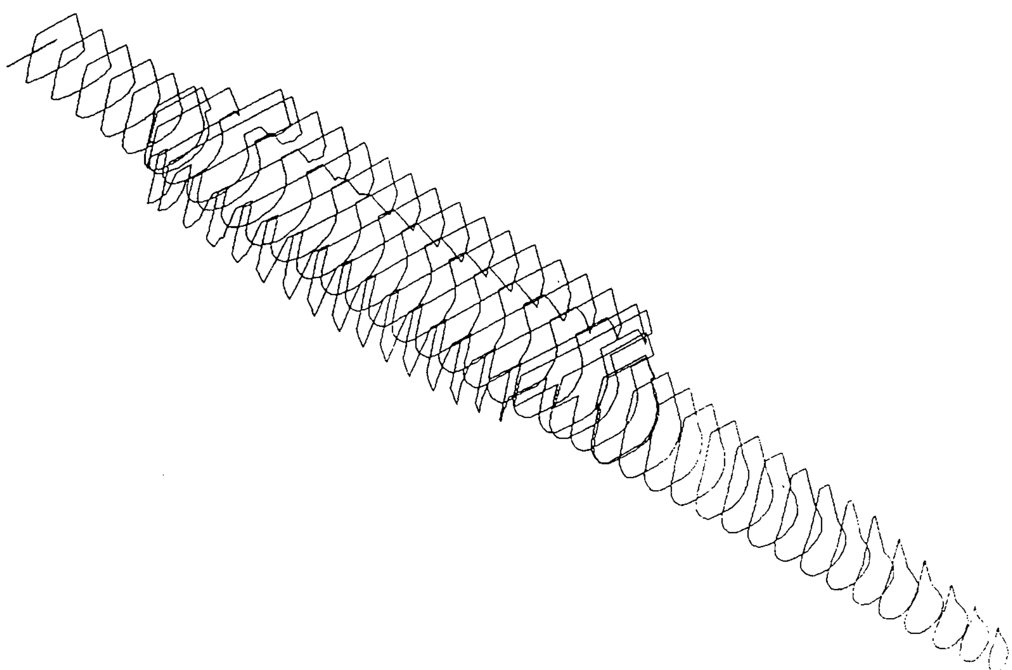

Figure 1. Trimaran Baseline Design

This design has several positive characteristics: potentially enhanced survivability, greater stability, larger beam (permitting better topside and second deck arrangements), and better seakeeping are only a few.

One of the primary attractions of the trimaran is enhanced survivability against sea-skimming missiles. By placing vital spaces in the center hull and those of lesser importance in the side hulls, a buffer zone is created. This buffer zone places the likely point of impact of a missile significantly away from the center hull. The greater distance between the missile hit and the center hull should allow the damage to be kept away from vital spaces more easily. With the damage isolated to non-vital spaces it is more likely the ship will be able to continue its mission.

The much larger beam of the trimaran is also an attractive asset of the design. It allows for a large superstructure and a very large helicopter landing area. Now the sides of the ship and superstructure can be sloped for stealth purposes while still maintaining large interior volume. The wide beam also allows for a second deck that is over 60 feet wide. The trimaran's dimensions and characteristics allow the warship designer to propose layouts and capabilities which are very attractive to the navy.

The larger beam also creates a very stable platform, such that the draft of the center hull can be relatively shallow. The center hull is of the wave piercer design. This should allow the ship to slice through waves and reduce the pitching of such a relatively small, long ship. The lower resistance of a long slender hull is expected to offset the negative effects of the side hulls.

The added stability due to this larger beam is also apparent when the ship is damaged and flooding has occurred. This wide ship has greater overall stability and greater transverse stability. A trimaran will experience less heel angle when damaged. The critical stability case occurs when one side hull is flooded and the other, as well as the center hull, is light-loaded. This can easily be corrected by ballasting the two nondamaged hulls.

The trimaran being considered has a displacement of 4600 long tons. It is comprised of a long narrow central hull and two very slender side hulls. The side hulls' length is approximately 30% of the ship's and they are supported by a central box structure that spans the beam. The center hull has an overall length of 516 feet (481 ft at the waterline), a beam of 27 feet, and a 15.4 ft draft. Each side hill is 148 feet long, has a beam of 6 feet, and a draft of 6 feet. At the waterline approximately 13 feet separates each side hull from the center hull. Each side hull displaces 35 tons, or 0.775 % of the center hull displacement. The ship has an overall beam of 72.5 feet and a beam at the main deck of 63 feet. Figures 2 and 3 show the half-breadth, profile, and body plans.

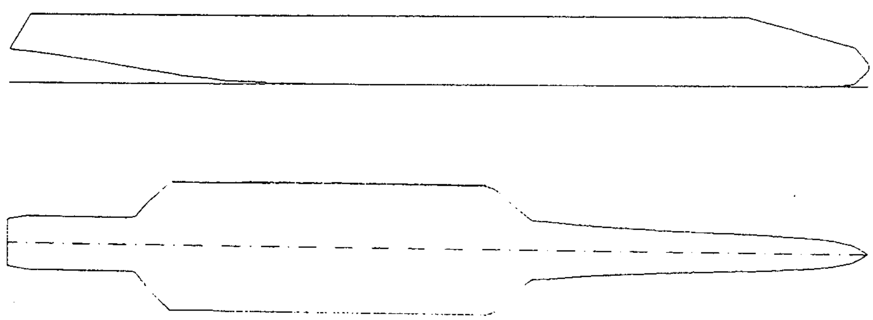

Figure 2. Baseline Design Half-Breadth and Profile Views.

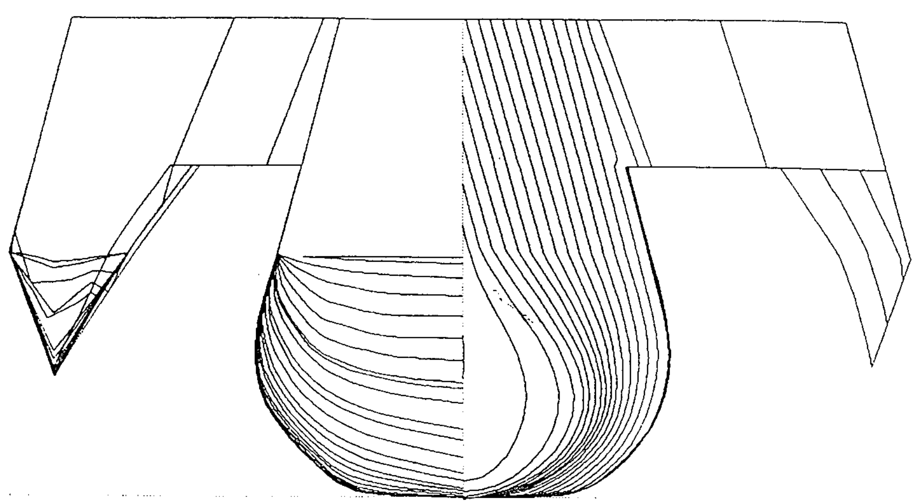

Figure 3. Baseline Design Body-Plan

The purpose of this thesis is to investigate how the resistance properties and power requirements of this design would change if side hull displacement were changed. The above described ship was used as a baseline, with the effect of increasing side hull displacements compared to this baseline. Larger side hulls would allow for greater displacement-more volume, more equipment, potentially greater mission performance, greater stability; but with a penalty. As the side hulls become larger, their resistance will rise and the ship's horsepower will need to increase. This thesis will provide an estimation of the horsepower requirement for a ship with greater displacement side hulls enabling one to decide if the benefits of larger side hulls overcome the penalty of more resistance. Model data from the Taylor Standard Series (Gertler 1954) and Series 64 (Yeh 1965) was used to determine the residual resistance coefficients and thereby allow an estimate of the required horsepower.

II. RESISTANCE

The resistance of a ship is the force that tends to impede its forward motion. Hydrodynamicists typically break resistance into two major components; frictional and residual, where the residual resistance is made up of wavemaking, eddy or viscous, viscous pressure, separation, wave breaking, and spray resistance. Determining resistance is the essential element in determining the power required to drive a ship.

Finding the resistance of a hull shape can be done three ways: prototype testing, model testing, or numerical or computer methods. Rarely is the ship designer allowed the luxury of a prototype, and computer methods are still much of an art form (Appendix B), so model testing is the normal route. However, model testing is an extremely expensive and time intensive process, requiring skilled craftsman and elaborate facilities. Therefore, in early design stages the data from other model tests, organized in an orderly "series" of tests, are frequently used to estimate resistance. It is this approach which is used in this thesis to investigate the effects of increasing side hull displacement.

At low speed, friction is the vast majority of resistance, while at higher speeds wavemaking and other viscous effects predominate. The International Tow Tank Conference (ITTC) 1957 model-ship correlation line is used to determine the frictional resistance coefficient. Two series

of model tests, the Taylor Standard Series and Series 64, are frequently used in the determination of residual resistance. These two series are used in this thesis to find residual resistance coefficients to allow the comparison of the effects of larger side hulls A correlation allowance of 0.4x10^-3 is used to take into account the difference in the roughness of models compared to actual ships. Air drag, although a factor as side hull dimensions increase, is not considered.

The Taylor Series and Series 64 are used to determine the bare hull calm water residual resistance of the individual hulls. When the hulls are joined together to form the trimaran, interference will occur. Interference is frequently used to describe the effects of the transverse and divergent wave systems of a hull combining. Here, interference is used to describe the effect the wave system of a hull has on another hull. This will be addressed later.

III. USE OF SERIES

A. OVERVIEW

While larger side hulls provide added space and stability, their increased displacement will also entail an increase in horsepower required. To determine the effect on horsepower of larger side hulls, the EHP required to drive them was determined using the Taylor Standard Series and Series 64. Neither series is fully applicable to these unusual hulls over the entire speed range of interest. However, a judicious use of both series will permit a useful estimate of the effect of varied side hull displacements on total ship resistance. The increase in side hull displacement was achieved by scaling the original offsets.

The commercial program General HydroStatics (GHS) was used to perform the scaling. The program is capable of scaling the values of the offsets. Transverse and vertical values for the side hull were scaled by an equal value. This yielded geometrically similar side hulls of several displacements, all greater than the original. The program was also used to calculate the displacement, volume, and surface area of the side hulls. Scaling was performed to result in side hulls whose displacement was 1, 2, 3, 4, and 5 percent of the center hull's. The original (unscaled) side hull has a displacement 0.775 percent of the center hull. The data obtained from the GHS program and the ships' dimensions were used to calculate required values and coefficients of form.

To estimate the effective horsepower (EHP, horsepower required to achieve a given speed) of the hulls, their characteristics were applied to the Taylor Standard Series and Series 64 data. Use of these two series enabled residual resistance coefficients to be found and EHP to be calculated. Residual resistance coefficients were determined for each hull (0.775, 1,2,3,4,5% and the center hull) at 17, 24.33, and 30 knots. Figure 4 depicts fthe five side hull variations overlaid on the baseline design (frame 273) for comparison. Table 1 presents measurements and coefficients of form used in the series.

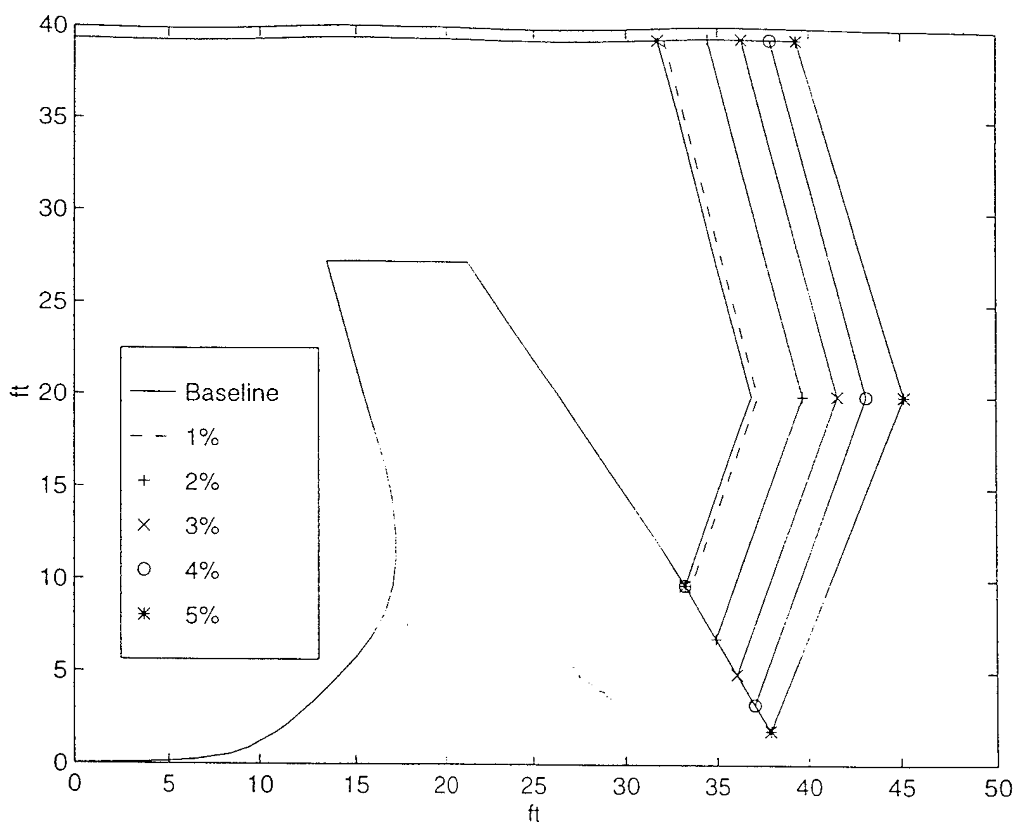

Figure 4. Relative Size Comparison of Increased Side Hulls to Baseline Design

Hull	disp. LT	length ft	beam/ draft	surface area sq ft	volume cu ft	Cp	Cb	Cv x10^-3
Center	4530	481.7	2.2	24271	158573	0.701	0.613	1.42
Side hull*								
baseline	35.1	148	1.02	1349	1404	0.573	0.284	0.43
1%	45.3	148	1.02	1433	1586	0.573	0.284	0.49
2%	90.6	148	1.02	2043	3171	0.573	0.284	0.98
3%	135.9	148	1.02	2516	4357	0.573	0.284	1.47
4%	181.2	148	1.02	2914	6344	0.573	0.284	1.96
5%	226.4	148	1.02	3271	7929	0.573	0.284	2.44

Table 1. Dimensions and Form Coefficients.
* Side hull values are for one side hull.

B. TAYLOR SERIES

The Taylor Series is an extensive compilation of data from the testing of a methodical series of ship models. It provides residual resistance coefficients over three beam-to-draft ratios (2.25, 3, and 3.75) and several volumetric coefficients. Results obtained from the series provided an estimation of each hull's required EHP.

1. Center Hull

Based on the baseline ship's offsets and GHS results the center hull displaces 4530 tons and has a waterline length of 481.7 feet. This length results in relatively low speed-to-length ratios; 30 knots is a speed-to-length of 1.37 (Fr=0.41). The center hull's beam to draft ratio of 2.2 is just below the smallest Taylor Series ratio of 2.25. Residual resistance coefficients were found for 17, 24.33, and 30 knots and were then used to find EHP.

2. Side Hulls

The side hulls are extremely slender and shallow for their length (148 feet); the baseline side hull has a beam of 5.8 feet and a draft of 5.7 feet. Taylor Series data only covers speed-to-length ratios up to two. Therefore, EHP based on Taylor Series was calculated up to 24.33 knots (speed to length of 2.0, Froude number Fr=0.6). Residual resistance coefficients are available for volumetric coefficients from 1x10^-3 to 5x10^-3, however they are not available for all volumetric coefficients above a speed-to- length ratio of 1.2. The largest side hull considered, 5% of center hull displacement, has a volumetric coefficient of 2.4x10^-3. The residual resistance coefficient curve for volumetric coefficient equal to 2.5x10^-3 ends at a speed to length of 1.43 (17.4 knots), therefore 17 knots was chosen for evaluation. For the 24.33 knot calculation for the 5% side hull, the last residual coefficient plotted for volumetric coefficient equal to 2.5x10^-3 was used. Based on the curves

presented for other volumetric coefficients this value appears to be a reasonable approximation for the residual coefficient at 24.33 knots and should result in a value that is only slightly below what the actual value would be.

The smaller side hulls, 0.775, 1%, and 2% have volumetric coefficients of 0.433×10^{-3}, 0.489×10^{-3}, and 0.978×10^{-3} respectively. The Taylor Series' lowest volumetric coefficient is 1×10^{-3}; the residual resistance coefficient for this value was used for the 0.775, 1%, and 2% side hull EHP calculations. This will result in an overestimation of EHP for these three size side hulls.

C. SERIES 64

Series 64 consists of tests of high speed displacement forms evaluated at speed-to-length ratios up to 5.0. The series was conducted to accumulate data at high speed-to-length ratios since most earlier tests did not exceed ratios of two. In the series, residual resistance coefficients are provided for three beam-to- draft values (2, 3, and 4) over several displacement-to-length ratios. All models tested in the series had a prismatic coefficient of 0.63. For this thesis, Series 64 displacement-to-length ratios were converted to volumetric coefficients to enable Series 64 data to be used in the same manner as the Taylor Series.

1. Center Hull

The center hull EHP for the three speeds was also calculated utilizing Series 64 data. The hull's prismatic

coefficient of 0.7 is slightly higher than the 0.63 of Series 64. Other parameters of the center hull match well to Series 64 allowing for residual resistance coefficients to be directly estimated.

2. Side Hulls

The side hulls' small size fit nicely to Series 64 data. The smaller displacement-to-length ratios converted to four volumetric coefficients below 1x10^-3, the smallest being 0.52x10^-3. This small value matched very well with those of the 0.775 and 1% side hulls. Series 64's largest displacement-to- length ratio yielded a volumetric coefficient of 1.92x10^-3. Residual resistance coefficients obtained from this value were used for the 4% and 5% side hulls. Series 64's broad range of speeds (speed-to-length ratios up to five are provided) enabled this series to be used for side hull speeds of 30 knots, speed-to-length of 2.47 (Fr=0.73).

IV. RESULTS

As expected, side hull EHP increases with greater side hull displacement; however analysis of the results shows that there may be attractive benefits to the ship designer from increased side hull size. As side hull displacement is increased to 1, 2, 3, 4, and 5 percent of center hull displacement this corresponds to side hull displacements that are 129, 258, 387, 516, and 645 percent of the baseline side hull displacement. The larger displacement side hulls have volumes that are 113, 226, 339, 452, and 565 percent of the baseline. This additional volume and displacement may enhance the already mentioned attractions of a trimaran. EHP values are tabulated on Table 2; while EHP, volume, and surface area values as a percent of the baseline are tabulated in Table 3 for each side hull variation.

	Center hull	Baseline side hull	1% side hull	2% side hull	3% side hull	4% side hull	5% side hull
Taylor							
EHP * 17kn	2465	208	222	316	494	696	922
24.33 kn	10861	623	662	943	1363	2132	2869
Ship EHP 17kn		2882	2908	3097	3452	3858	4309
24.33 kn		12107	12185	12748	13558	15125	16598
Series 64							
EHP* 17kn	3668	181	192	339	543	676	759
24.33 kn	12898	478	508	900	1386	1780	1998
30kn	25746	860	913	1482	2228	2831	3178
Ship EHP 17kn		4030	4053	4346	4755	5020	5185
24.33kn		13855	13915	14697	15670	16457	16893
30 kn		27465	27573	28709	30202	31408	32101

Table 2. Effective Horsepower (EHP).
* Side hull values are for one side hull.

	1% side hull	2% side hull	3% side hull	4% side hull	5% side hull
volume	113	226	339	452	565
surface area	106	151	186	216	242
Taylor					
EHP* 17kn	106	151	236	334	442
24.33kn	106	151	218	342	460
Ship EHP 17kn	101	107	120	134	150
24.33 kn	101	105	112	125	137
EHP/ton* 17kn	82	59	57	66	69
24.33kn	82	59	61	65	71
Ship EHP/ton 17kn	101	105	115	126	138
24.33kn	101	103	107	117	127
Series 64					
EHP* 17kn	106	187	300	373	419
24.33kn	106	188	290	372	418
30kn	106	172	259	329	370
Ship EHP 17kn	101	108	118	125	129
24.33kn	101	106	113	119	122
30kn	101	105	110	114	117
EHP/ton* 17kn	82	67	67	64	57
24.33kn	82	73	75	72	65
30kn	82	73	78	72	65
Ship EHP/ton 17kn	101	105	113	117	119
24.33kn	100	104	108	112	113
30kn	100	102	105	108	108

Table 3. Percent of Baseline Design.
* EHP and EHP/ton values are for one side hull.

A. TAYLOR

Figure 5 shows that as displacement increases so does EHP.

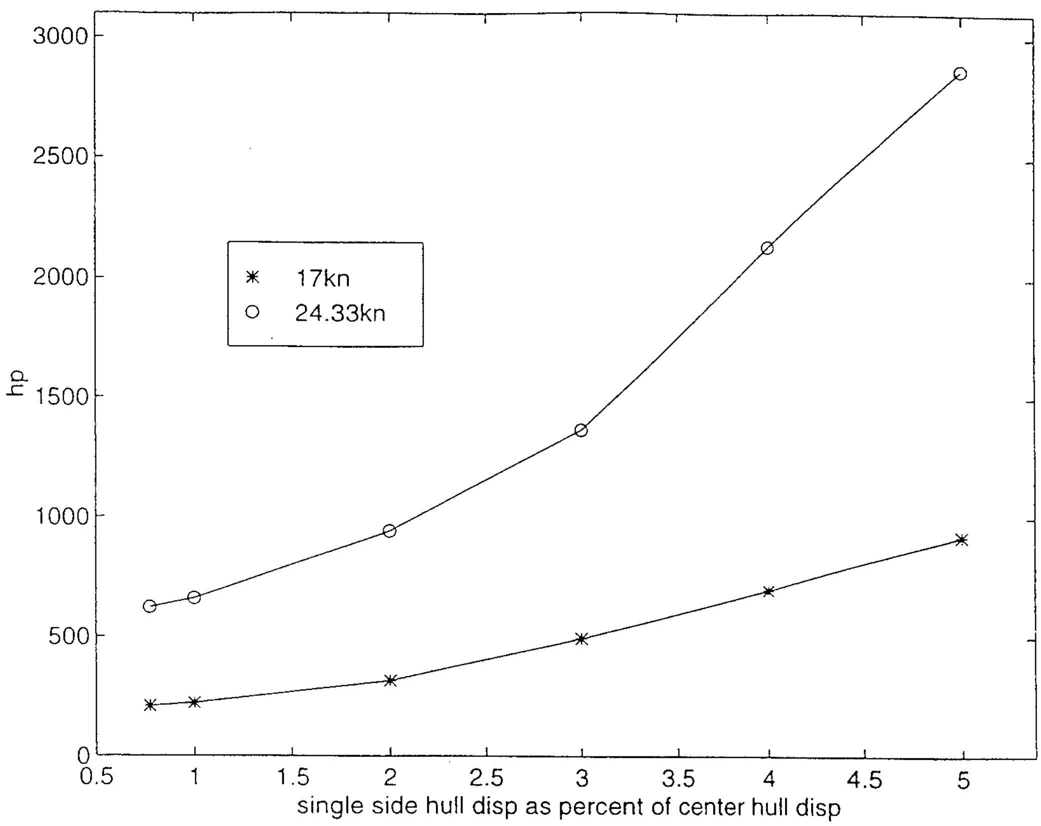

Figure 5. Single side hull EHP vs side hull percentage based on Taylor Series.

This increase is due to the increase in surface area and residual resistance coefficient, the latter having the greater effect. The combination of the EHP values for side hulls and the center hull is presented in Fig. 6.

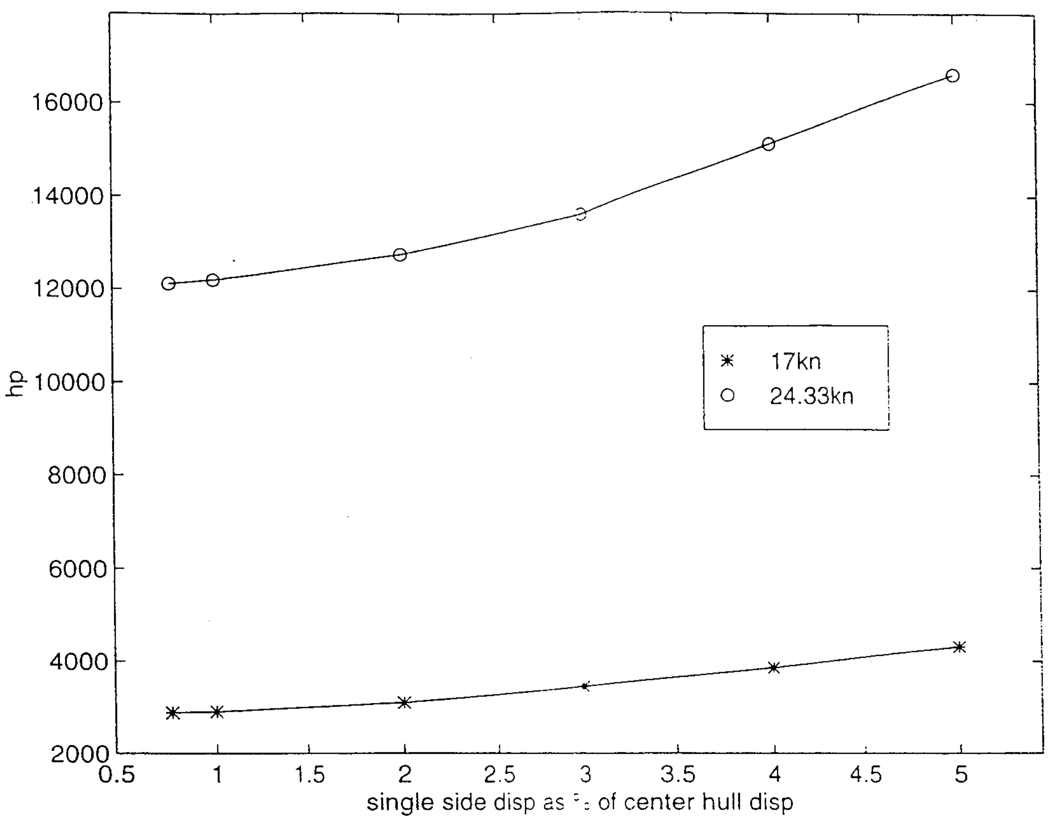

Figure 6. Ship EHP vs Side Hull Displacement Percentage Based on Taylor Series.

The figure shows that ship EHP increases as displacement increases, as expected. A more interesting presentation of the results is Fig. 7, side hull EHP/side hull displacement vs displacement percentage.

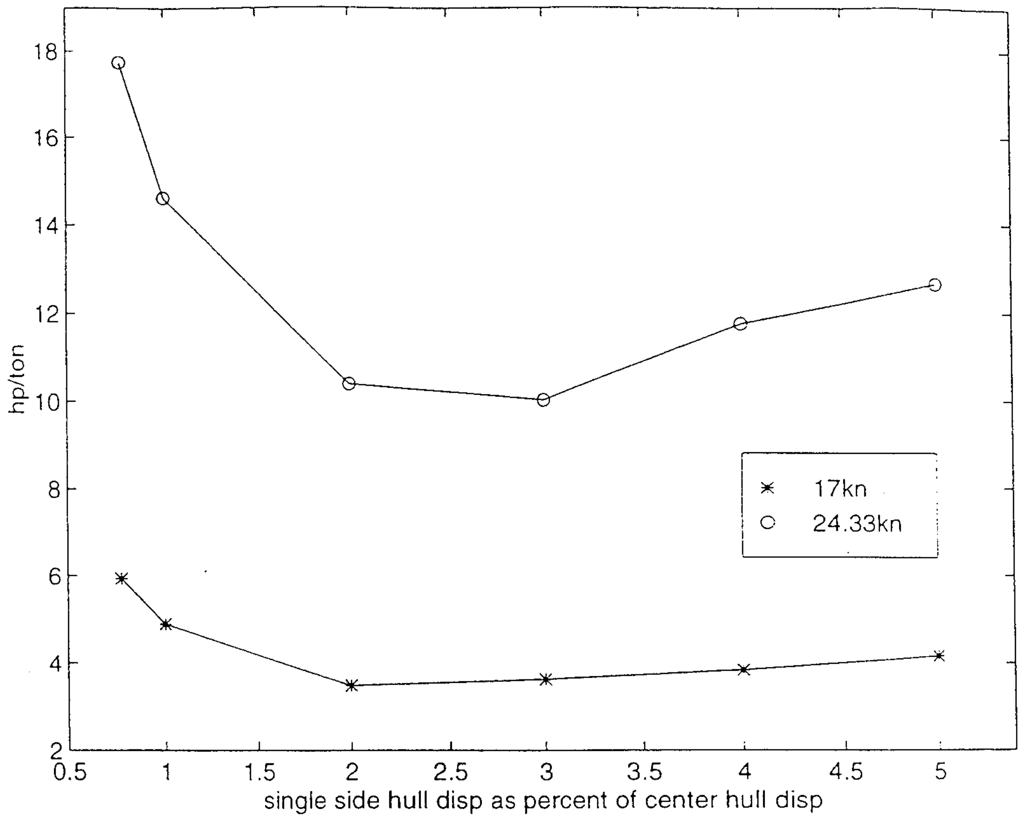

Figure 7. Single Side Hull EHP/Ton Side Hull Displacement Vs Side Hull Displacement Percentage Based on Taylor Series

This figure shows that EHP/ton decreases as side hull displacement increases. The gain in displacement more than offsets the increase in EHP. Figure 8 is ship EHP/ton of ship displacement vs displacement percentage.

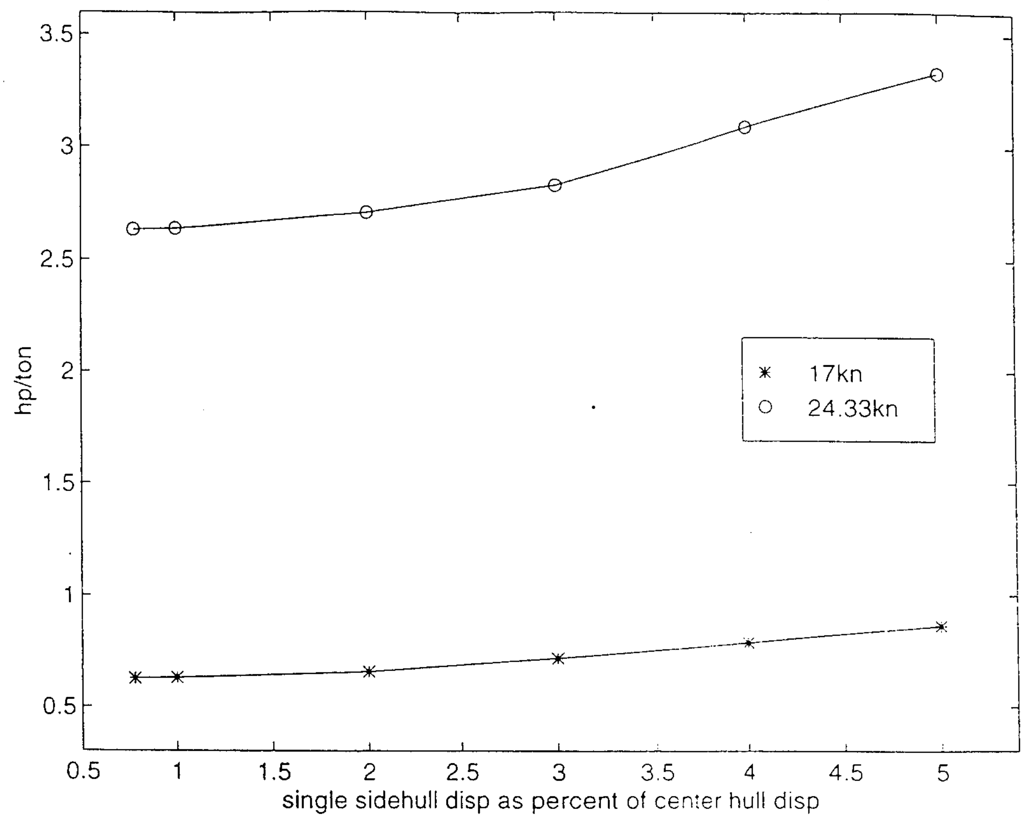

Figure 8. Ship EHP/Ton Ship Displacement Vs Side Hull Displacement Based on Taylor Series

It is very similar in shape to Fig. 6 , however the values show an interesting trend. The percentage increase in EHP/ton is much less at 24.33 knots than at 17 knots. This figure also shows that for a small EHP/ton penalty a significant increase in side hull displacement is possible.

B. SERIES 64

Side hull EHP vs side hull displacement based on Series 64 calculations are shown in Fig. 9.

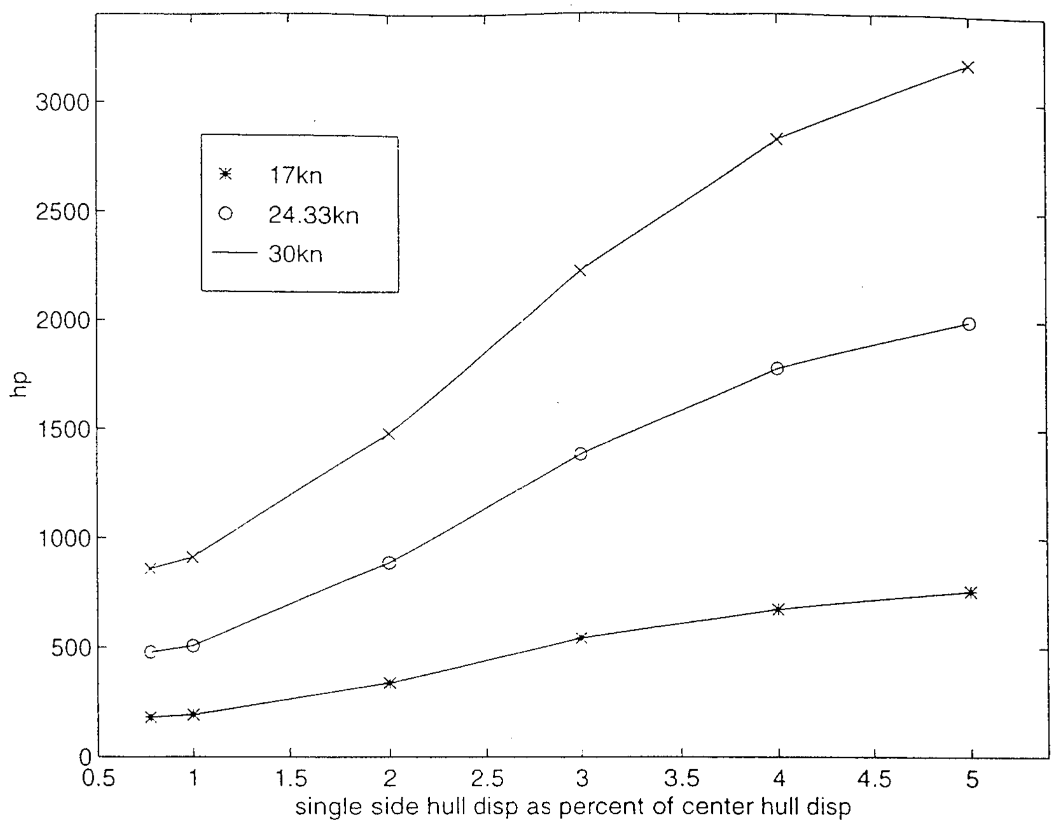

Figure 9. Single Side Hull EHP Vs Side Hull Displacement Percentage Based on Series 64

EHP increases with displacement; however the percentage increase for 30 knots is less than for 17 or 24.33 knots. The plot of ship EHP vs side hull displacement percentage, Fig. 10, also shows this trend.

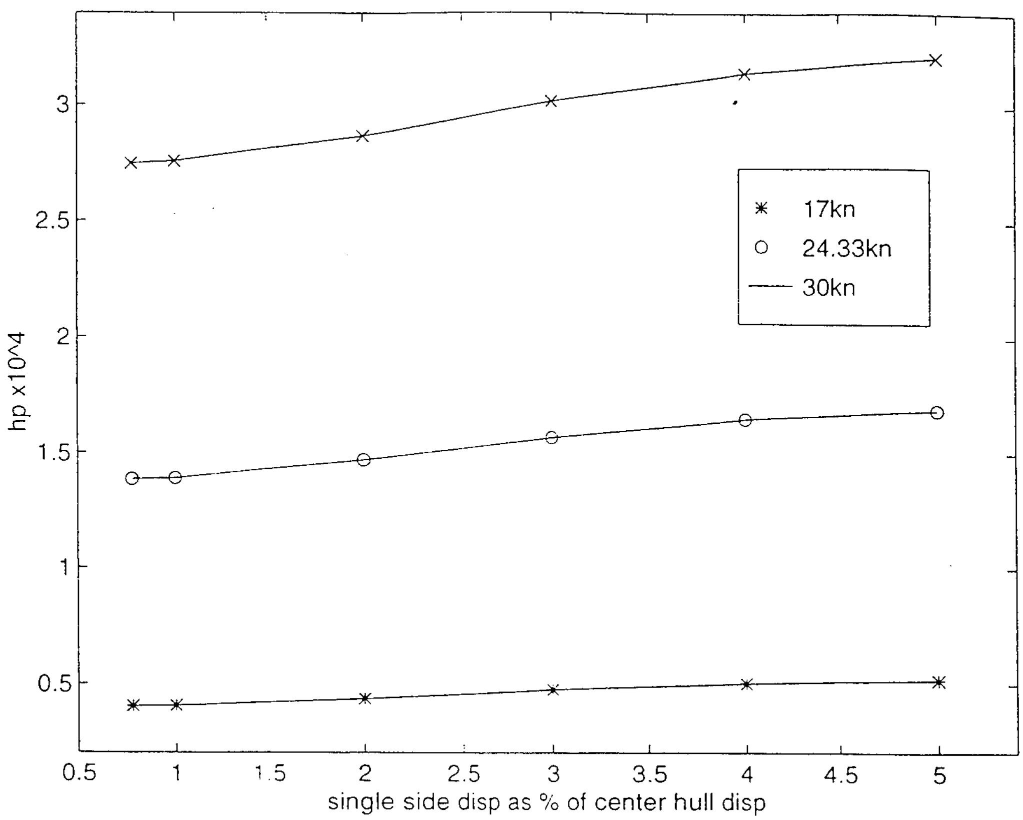

Figure 10. Ship EHP Vs Side Hull Displacement Percentage Based on Series 64

The percentage increase in EHP is much less as speed increases, although the magnitude of the increase is higher as speed increases.

Figure 11, side hull EHP/side hull displacement vs. displacement percentage, again shows that EHP/ton drops and then climbs slowly as displacement increases.

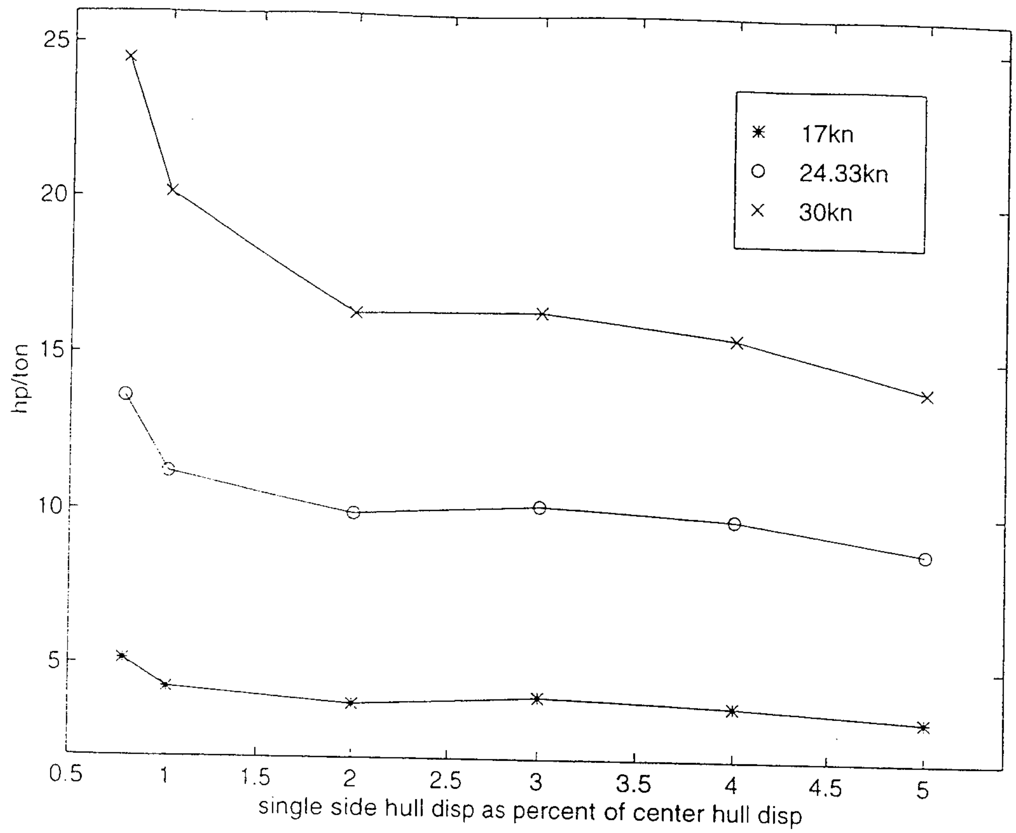

Figure 11. Single Side Hull EHP/Ton Side Hull Displacement Vs Side Hull Displacement Percentage Based on Series 64

However, Series 64 calculations show that the curve then drops. This trend may be attributed to the residual resistance coefficient being based on a lower value of volumetric coefficient than the actual value for the four and five percent displacement calculations. Ship EHP/ship displacement vs displacement percentage, Figure 12, shows that the percentage increase in EHP/ton is less the higher the speed.

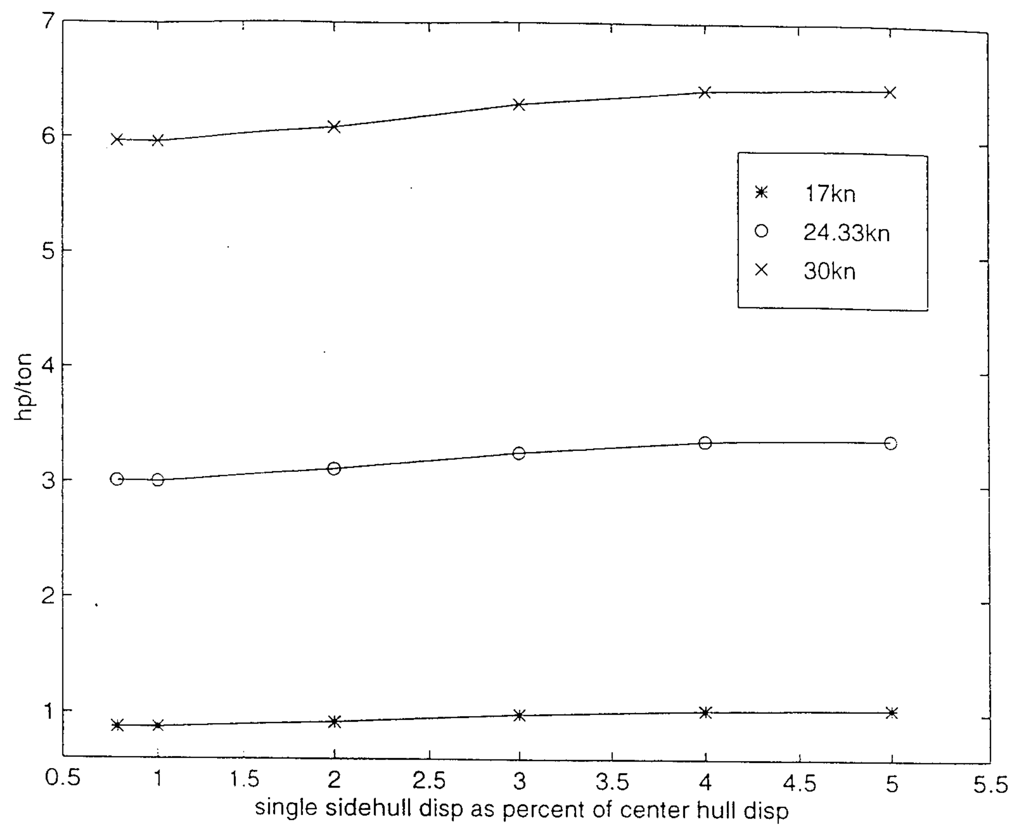

Figure 12. Ship EHP/Ton Ship Displacement Vs Side Hull Displacement Percentage Based on Series 64

Analysis of calculations based on Taylor Series and Series 64 shows that an increase in side hull displacement to one to three percent of center hull displacement will yield much greater side hull volume and displacement with a small horsepower penalty. Both series show that the percentage

increase in EHP due to increased displacement is less at higher speeds, although the magnitudes of EHP are higher. Side hull EHP calculations suggest that the Series 64 parent form may be more efficient than the Taylor Series parent. A direct comparison of ship EHP based on the two series was not performed due to the difference between the two series for center hull EHP and the effect this had on values. The results of calculations suggest that by increasing side hull size the ship designer may gain significantly more volume and displacement while incurring a small power penalty.

V. INTERFERENCE

Interference is typically defined as the combining of the divergent and transverse wave systems of a hull. In this work it is used to describe the combining of effects of one hull's wave system with another's. Interference may be negative, the ship's resistance is less than the sum of the hulls individually; or positive, the ship's resistance is greater than the sum of its hulls individually. To investigate the effects of interference on the trimaran a search of relevant work was conducted. The literature search yielded little published work on trimarans, however catamarans and SWATHS were well documented, although primarily at lower Froude numbers.

The interference experienced by catamarans is divided into two parts; viscous and wave. Viscous interference is due to asymmetric flow about a hull caused by the presence of the other hull and the effect this has on the boundary layer and the formation of vortices (Insel 1992). Insel found that viscous interference is more a function of length-to-beam ratio than speed or hull separation with long slender hulls preferred.

Catamarans experience wave interference as described above. Typically negative interference is the result of the cancelling of part of the divergent wave system while positive interference stems from the interactions of transverse systems

(Everest 1968). Wave interference is a function of speed and separation of a particular set of hulls. Many reports have concluded that larger separation distances yield reduced wave interference. Insel, Everest (1968), and Tasaki (1963) determined that negative interference was possible in the range $0.3<Fn<0.4$ when hull separation was approximately 30-35% of hull length; however, at other speeds interference would be positive. Insel also described how the humps and hollows of the resistance versus Froude Number curve can be moved by changing the length-to-beam ratio and hull separation. He also found that above a certain speed interference is independent of length-to-beam ratio and hull separation.

Insel (1992), Everest (1968), and Tasaki (1963) were able to accurately predict the Froude region in which negative interference was possible, but theoretical calculations overpredicted what was achieved experimentally. Tasaki (1962) found that asymmetrical hulls (inner surfaces were flat) are inferior to symmetrical hulls with regard to interference. He also concluded that the ratio of resistance increase caused by interference to individual hull resistance is not affected by draft.

The trimaran's novelty is shown by the lack of published work. Everest found that the location of side hulls in relation to the center hull, particularly fore-aft placement, will determine the positive or negative effects of interference. Cudmore (as presented by Andrews (1995)) has

probably performed the most useful body of work. He performed model tests in which side hull fore-aft location and separation was varied. His results were reported as showing that the added resistance due to interference was generally 10% of the sum of the hulls' individual resistances, only occasionally more and sometimes less; and this increased resistance appeared to be more apparent above 20 knots. Although the model used by Cudmore is not like this design, its long slender center hull and fine side hulls are most likely similar enough to apply his resultsas a first-order approximation.

The basic difference between catamarans and trimarans is the long center hull and its resulting wave system. How this wave system affects the side hulls is largely unknown. It is possible to design a trimaran so that negative interference is present. However, it is much more likely that design considerations of stability, overall size, and weight will dictate the location of the side hulls. How this unique trimaran is affected by interference is unknown. There is little available research on trimarans. Based on what is available, it seems reasonable that interference will result in an additional 10% in EHP above individual bare hull values and that a design for negative interference may be impractical, although neutral interference at a single speed may be possible.

VI. CONCLUSIONS

The trimaran analyzed here is a unique design whose wide beam, stability, and potentially enhanced survivability make it an attractive warship. The primary conclusion of this thesis is:

- That a small increase in side hull displacement will achieve significantly more usable volume with only a small EHP penalty, predominantly at higher speeds.

Other conclusions are:

- Based on available work, interference effects generally result in the addition of approximately 10% to the ship's EHP above the sum of the hulls' individual EHPs.
- While it may be possible to design for negative or neutral interference at a specified speed; other design considerations such as stability, overall size, and weight will most likely govern decisions.
- Keeping the side hulls as fine as possible permits low wavemaking resistance and interference.

VII. RECOMMENDATIONS

Based on the research and analysis performed during this thesis, it is recommended that:

- For this model consider combining the use of the Taylor Standard Series for center hull EHP predictions and Series 64 for side hull predictions at all speeds.
- Continue to investigate the effects of interference using Renyolds-averaged Navier Stokes (RANS) or another Computational Fluid Dynamics (CFD) code.
- Perform model tests on the baseline design and variations suggested by RANS work to investigate the effects of side hull size, separation, and placement.

APPENDIX: COMPUTATIONAL FLUID DYNAMICS

Computer modeling of ships is a very attractive prospect: the thought that a few hours on a computer could replace the enormous cost of time and money in tow tanks is appealing. Although computational fluid dynamics has not reached this point, it may be a useful tool to the designer. In an attempt to determine how interference would affect EHP, the use of a Reynolds-averaged Navier-Stokes (RANS) code was investigated.

The RANS code used was developed by the Iowa Institute of Hydraulic Research (The University of Iowa) sponsored by the Office of Naval Research. It solves the Reynolds-averaged Navier-Stokes and continuity equations using the Baldwin-Lomax turbulence model. The code can be used to determine frictional and pressure coefficients and the wake and wave system at steady state. The code can also take into account the effects of a propeller.

Although time precluded obtaining presentable results; it is believed that the use of this or a similar code would prove useful. Different side hull sizes and locations (hull separation, fore-aft position) may be tried on a computer to determine which variation warrants tow tank testing. This may reduce the cost and complexity of model testing.

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